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ANALYSIS OF THE ARPA SATELLITE CIRCUIT BETWEEN ETAM, W. VA., AN--ETC(U)

JAN 77 S ROTHSCHILD, E HOVERSTEN F44620-76-C-0045

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This report describes the work performed in support of the ARPA packet satellite experiment. Test results on the satellite circuit and the modifications incorporated into the channel modem as a result of those tests are presented. Also discussed are new interface units which can increase the information throughout by as much as 20%. New test and monitor faciliites are also presented.

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1. Introduction and Summary

This final report will describe the work performed by the Communications Satellite Corporation, COMSAT, under Contract No. F44620-76-C-0045, entitled "Worldwide Seismographic Communications Network", sponsored by the Advanced Research Projects Agency, ARPA Order No. 2298. The purpose of the program was to assist ARPA and provide support to NMRO for the expansion of the ARPANET to those countries from where seismic data will be returned to SDAC via satellite, utilizing packet switching technology. The total cost of the contract was $53,122. The effective data of the contract was November 1, 1975, with a performance period extending from the effective date through May 15, 1976. In June, 1976, the contract period was extended through September 30, 1976.

Although this experiment could have been performed on SCPC (Single Channel Per Carrier) equipment as well as pre-assigned SPADE, it was decided to use the SPADE terminal because: (1) the SCPC terminal at Etam had not been contractually accepted at that time, and (2) no SCPC terminal was available at Goonhilly. Even if the SCPC terminal at Etam could have been used, because of the experimental nature of the program, it was felt that more reliable information could be obtained by employing the same type of terminal at each end of the satellite link.

The efforts under this contract have provided support to the ARPA Packet Satellite Experiment. This experiment has the objective of testing a number of demand access techniques over a satellite channel between Etam, West Virginia, and Goonhilly, England. The satellite channel is realized through the use of a 38 KHz channel in the SPADE transponder (Transponder 10) of the INTELSAT Atlantic primary satellite. The equipment required at each earth station includes a satellite interface message processor (SIMP), two SPADE channel units, and a SIMP-SPADE Interface (SSI) unit.* The SPADE channel unit interfaces to the SPADE system common equipment at IF and this common equipment is used to provide the necessary IF to RF conversions. Comsat designed and supplied the SSI at Goonhilly under a previous contract. An SSI using the same design was implemented at Etam as part of the channel tariff.

The study effort performed under the present contract was divided into two general areas: direct engineering support of the ARPA Packet Satellite Experiment and design efforts to improve system hardware. The area of direct engineering support involved a number of activities to improve and understand the channel performance in this type of application and assess any impact of channel performance on the experiment.

Specific types of activities conducted under this phase of the program includes coordination with Bolt, Beranek and Newman on the performance of channel tests between the earth stations and the interpretation of experimental data, designing, scheduling and monitoring tests performed on the satellite channel, and directing tests on the SPADE channel units to better understand their operation and to facilitate any required design changes. A direct result of monitoring the channel performance was a determination that the packet type of operation required very stringent control of such system parameters as power and frequency. Earth station procedures were changed so that the channel is now monitored daily

*See Annex 1 for a list of definitions

by the earth station personnel to insure that both frequency and power levels are maintained within the system specifications. As a result of tests performed on the SPADE channel units, a better understanding of the constraints placed on the system performance was realized. Specifically, the effects of differences in power level and frequency offsets on the modem operation were determined. Additional testing on the AGC circuitry resulted in a redesign of the circuit that greatly improved the operation of this subunit and permitted the channel to be used for experiments that involve contention demand assignment protocols.

The engineering support activity was conducted in parallel with the second area of investigation, viz., the considerations of system hardware design changes which could improve system performance with a resulting increase in the scope, flexibility, and realism of the experimental activities. This second area of support resulted in a completely new SIMP-SPADE interface design. The new design removes certain operational constraints, provides improved flexibility in use of the channel, and increases the channel bit rate from 56 KB/s to 64 KB/s. The new interface design is discussed in greater detail later in this report.

Approximately 60% of the effort was spent in direct engineering support of the satellite experiment, including coordination, testing and monitoring. Another 30% of the effort was spent studying means for improving the system performance including design of the new interface, and the remaining 10% was spent in miscellaneous tasks related to the overall program; e.g., training personnel at the earth stations in regards to system operations, preparing reports, and holding discussions with ARPA relating to future performance requirements and implementation.

The Atlantic Packet Satellite Experiment, including the activities under this contract, has demonstrated that the transmission of packet data via satellite is feasible. The activities during this study period have indicated the strong desirability of implementing a real time test and monitoring capability as an integral part of the experiment to help in increasing channel reliability and understanding the experimental data. Further the study activities have provided the basis for the implementation of an improved interface design which will improve the reliability, flexibility and throughput of the channel.

In the next section the operation of the initial system implementation will be briefly described. Some of the problems which arose due to the packet mode of operation and the actions taken to ameliorate them will also be considered. Some SSI modification will also be described. The use of channel monitoring as a diagnostic tool will be considered. Finally, the remaining channel performance problem will be mentioned, along with some analysis which supports the hypothesis that the problem results from the failure of the SPADE channel unit to reliably acquire each packet during the preamble under certain channel conditions.

Section 3 will be concerned with the system hardware design efforts carried out under the contract. The motivation for these efforts will be discussed. Design efforts to develop a new SIMP/SPADE Interface unit and to examine possible approaches of reducing, from two to one, the number of SPADE channel units required at each earth station will be discussed. Finally, the utility of encorporating a test and monitoring capability into the basic SSI will be considered.

2.0 Direct Engineering Support

In this section the initial system implementation and operation will be described to provide background for a discussion of some of the modifications that were made and for the discussion of the new SSI design which occurs in the next section. In the context of this operational framework, the discussion will consider some of the channel performance problems noted during the test and monitoring activities and also the various equipment and procedural modifications made to overcome these problems. The use of real time channel monitoring data in the diagnosis of channel problems will be discussed along with the remaining channel problems.

2.1 Initial System Implementation and Operation

The major emphasis in the implementation of the initial experimental configuration was to use a low risk approach, so that a minimum amount of modification to the baseband equipment of the SPADE channel units would be required. The SPADE system was originally designed for the transmission of voice data in a burst mode, i.e., the satellite power is utilized only during periods of actual voice activity. The ARPA Packet Satellite Experiment also requires a burst mode of transmission, but with data actuation. For this reason the SPADE system was chosen for use in the ARPA experimental program, with the interface so configured that it simulated a voice activated system. However, since the SPADE system is very complex, and is being employed in a manner not required for the transmission of voice, some problems occurred which could not be anticipated at the start of the program.

2.1.1 System Configuration

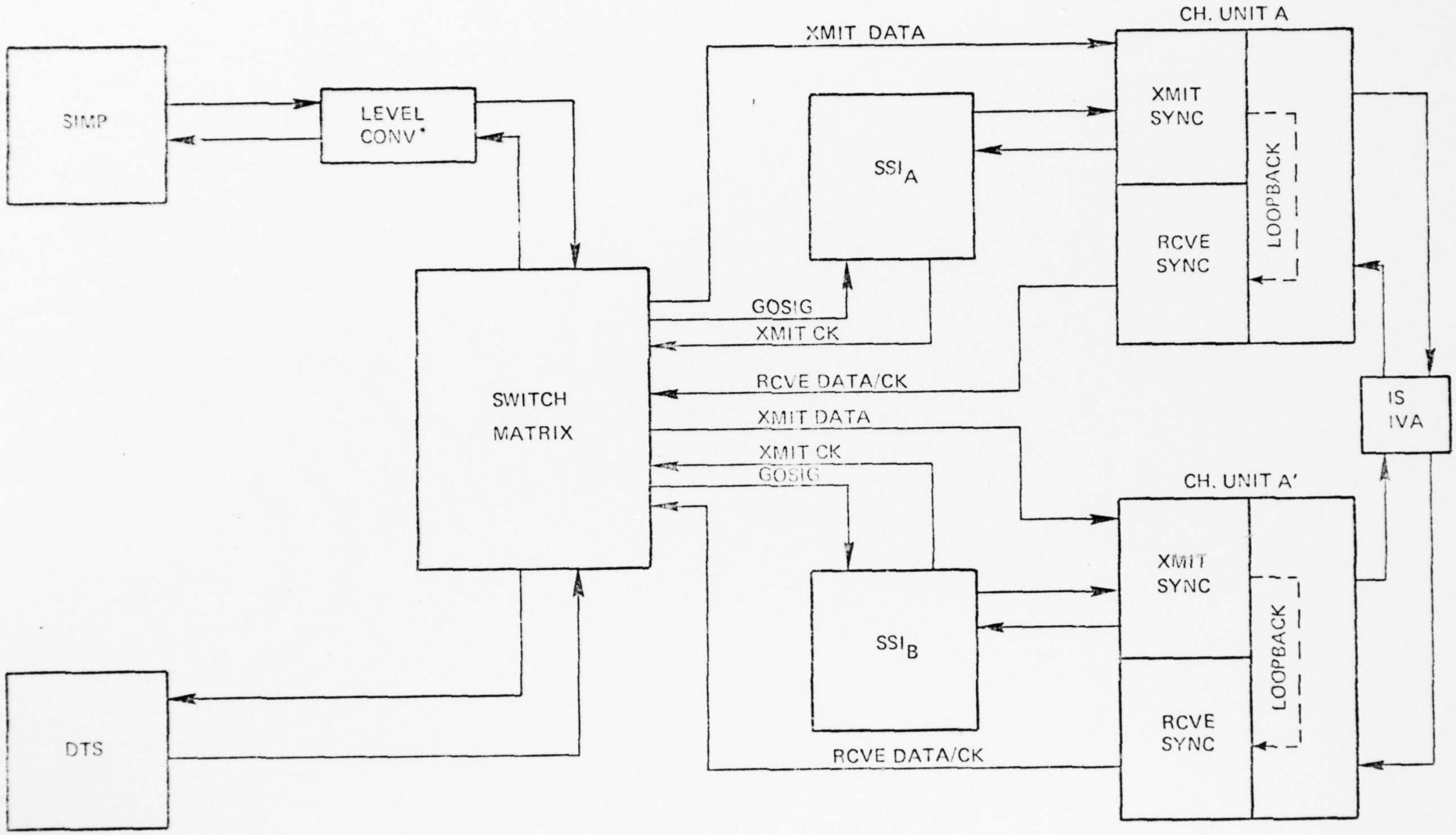
Figure 2-1 shows how the SIMP*, SSI, DTS, and SPADE channel units are connected into an integrated system at each earth station. In this configuration two SSI's and two SPADE channel units are used. One SSI is used for operation with the on-line transmit and receive synchronizers, and the other is available for use with the Data Test Set and as a spare. The switch matrix is provided so that in the event of a failure in the operational channel, switch-over to the standby channel can be accomplished with a minimum interruption of service. This configuration allows a failed unit, SSI or transmit or receiver synchronizer, to be removed and repaired.

During normal operation the SIMP is connected to transmit synchronizer A and receive synchronizer A' through SSI_A. The DTS will operate with transmit synchronizer A' and receive synchronizer A through SSI_B. The connection of the SIMP, DTS, and SSI's can be interchanged through the operation of the switch matrix. If loop back tests are to be performed, all data to and from the SIMP will pass through one SPADE channel unit, while all data to and from the DTS will pass to the other channel unit. During such loopback testing, there is no transmission to the satellite from either channel unit.

2.1.2 System Operation

The SPADE system was originally designed to convert 4.0 kHz terrestrial voice-band analog signals to 56 Kb/s PCM data using 7 bit encoding at an 8 kHz sampling rate. For packet data operation the SIMP

*See Annex 1 for list of definitions. A more detailed explanation of the system configuration and operation is available in the final report of Contract No. F44620-74-C-0070.



*CONVERSION FROM 303C LEVEL TO TTL LEVEL OR TTL LEVEL TO 303C LEVEL.

FIGURE 2-1 INTEGRATED SYSTEM

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substitutes data for PCM voice and transmits and receives data at 56 Kb/s to and from the SPADE channel unit. The SPADE PCM voice CODEC is bypassed and the data is fed directly into the Transmit Synchronizer and received directly from the Receive Synchronizer.

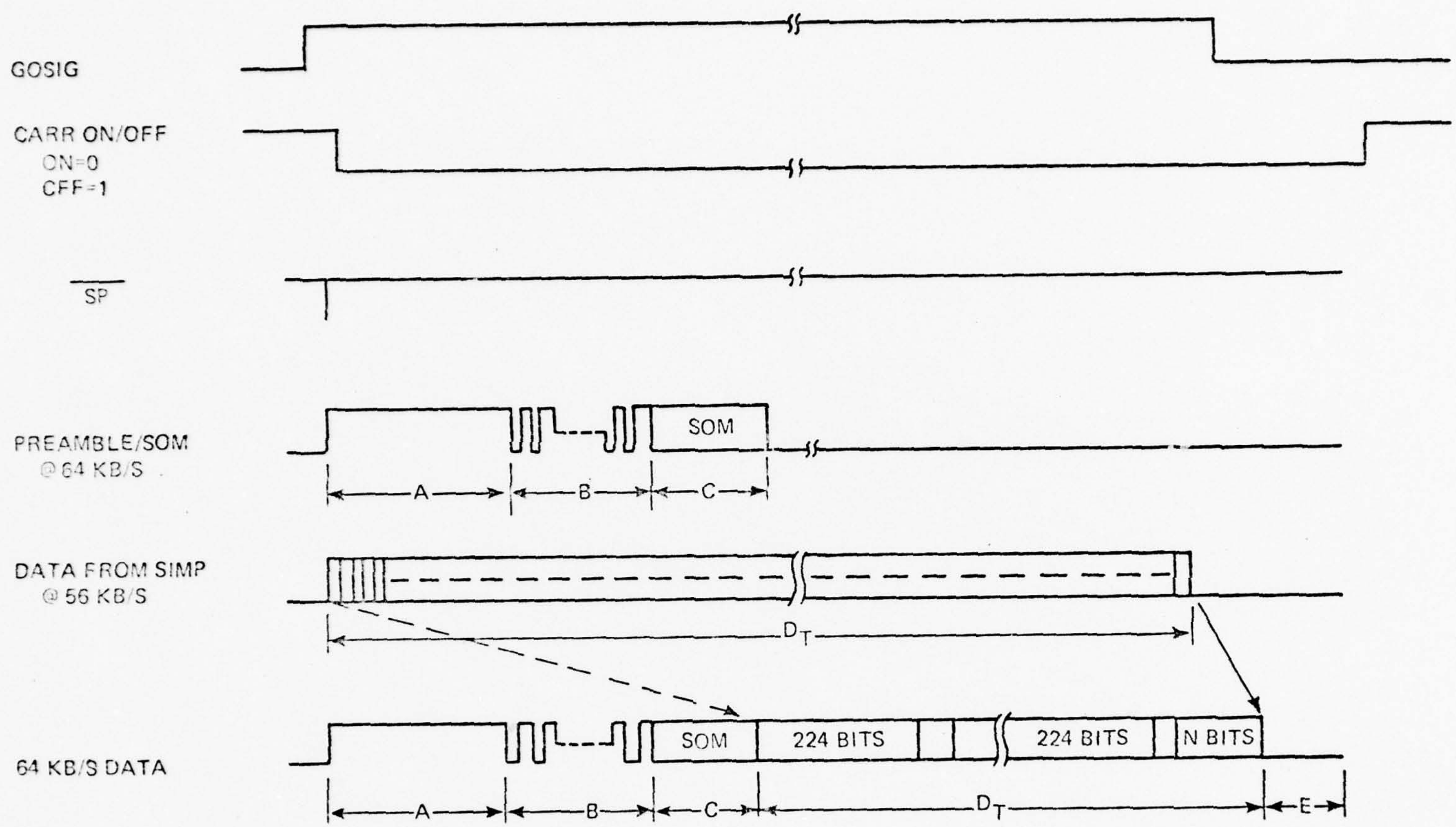
During normal operation, bursts of data are transmitted. Each data packet can vary in length from as little as approximately 100 bits to more than 1000 bits The time between bursts can also vary, with the lower limit set by the minimal guard band. The exact data format of a packet is dependent upon the particular system protocols being used and is essentially determined by the software programmed into the SIMP. In each burst the actual data packet is preceded by preamble and SOM bits which are used by the SPADE modem to acquire timing. The timing of the transmission of a burst from an earth station is controlled by the corresponding SIMP which initiates a burst by transmitting a GOSIG to the SSI. The SIMP's maintain a common time base through the use of a 'follow the leader' slotting algorithm. Basically both SIMPs periodically monitor their own round trip propagation time to the satellite and the second (slaved) SIMP monitors both its own and the other SIMP's transmissions to adjust its clock to maintain a fixed relationship with respect to the other SIMP, the leader. Thus the channel is slotted, i.e., packet transmissions can only start at a set of discrete times. Some of the protocols only allow a single station to transmit during a given slot while others, contention protocols, allow the possibility of both stations transmitting into a given slot. As will be explained below, channel modifications were required to obtain satisfactory performance with these contention protocols.

Once the SIMP has transmitted a GOSIG to the SIMP/SPADE Interface Unit (SSI), control of the channel unit and SIMP, i.e., time and rate for data sampled out of the SIMP, is maintained by the SSI. The SSI sends 56 kHz clock pulses to the SIMP. Data are sampled out of the SIMP at the 56 kHz rate and then stored in two 112 bit memories in the SPADE channel unit Transmit Synchronizer. The data are read out of the memories at a 64 kHz rate after the Preamble has been generated. The Preamble is composed of 40 bits for carrier recovery and 80 bits for bit timing recovery. After the bit timing recovery sequence has been generated, a 32 bit Start of Message (SOM) is inserted. This is followed by the data. Because the data are written into the memories at 56 kHz and read out at 64 kHz, the timing is such that 224 bits at 56 kHz equals 256 bits at 64 Khz. The 256 bits at 64 kHz is composed of 224 bits of data plus 32 bits of SOM. The 64 Kb/s serial data bits are converted into two parallel 32 Kb/s data streams for modulation of the carrier; 4ϕ-PSK modulation is used on a channel with a noise bandwidth is 38 kHz. The spacing between adjacent channels is 45 kHz.

The transmitted carrier must remain on until all data has been read out of the 112 bit memories. This is accomplished in the SSI by employing two sets of counters. The first set counts the number of data bits sampled out of the SIMP and passed on to the channel unit. This counter operated at 56 Kb/s. The second set counts the number of data pulses read out of the memories and operates at 64 Kb/s. When the second counter reaches the same number as the first, the carrier is turned off.

When the burst is received from the satellite, the inverse process is performed, i.e., the 4ϕ-PSK carrier is demodulated into two 32 Kb/s parallel bit streams which are interleaved to form a 64 Kb/s serial bit stream which is read alternately into one of two 112 bit memories at 64 Kb/s. The data are read out of these memories at 56 Kb/s; the SOM is stripped out of the bit stream during this operation. The operation of the Receive Synchronizer is controlled by the CARRIER ON gate generated in the receive modem. This gate allows the Read/Write memories to operate only as long as the carrier is present. To accommodate timing delays within the receive synchronizer, a 33 bit delay in addition to the 112 bit delays in the read/write memories, the transmitted carrier must remain on sufficiently long to ensure all memories have been cleared of received data. This requires the transmitted carrier to be on for approximately 2.5 msec after all data has been cleared out of memories in the transmit synchronizer. The carrier is held on for this additional time by presetting the 56 K bit counter at the transmit station to 140.

There has been some confusion as to why the SPADE channel carrier has to remain on for 4.5 msec after all the data has been sampled out of the SIMP. Figure 2-2 is a timing diagram showing the time relationship between the data and preamble, and the CARRIER ON/OFF signal. From the figure it can be seen that the carrier recovery sequence does not start until the start preamble pulse ($\overline{SP}$) has been generated within the transmit synchronizer. At the same time the first datum bit is sampled out of the SIMP and written into the first 112 bit memory. When this memory is filled, the data bits are held until the first SOM has been generated. This requires a total time of 2.375 msec. After the first SOM, 224 bits of data are read out, followed by a second SOM, and more data. The process continues until all data have been sampled out of the SIMP, written into the memory and then read out at 64 Kb/s. As previously mentioned, when the burst is received, the



A–CARRIER RECOVERY = .625 MSEC
B–BIT TIMING RECOVERY= 1.25
C–32 BIT SOM = .5 MSEC
E–140 BIT HANGOVER = 2.185 MSEC
TOTAL: A+B+C+E = 4.56 MSEC

FIGURE 2-2 TIMING RELATIONSHIP

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inverse process takes place. To insure that all the data received is read out of the memory of the Receive Synchronizer, the carrier must remain on at the transmit end for a sufficient length of time. The total delay in the Receive Synchronizer is 145 bits, composed of 33 bits for SOM detection plus one half of the 224 bits of memory. Taking some advantage of the "natural overhang time" in the receive modem, it was determined that 140 bits of additional on-time at the transmit station would be sufficient to insure all data would be read out of the receive memory. The 140 bits at 64 Kb/s requires an additional 2.185 msec. The total time that the carrier must remain on is the sum of preamble time (P_T), data time (D_T), plus overhang time (O_T), i.e.,

$$\begin{aligned} T &= P_T + D_T + O_T \\ &= 2.375 + D_T + 2.185 \\ T &= 4.56 \text{ msec} + D_T \end{aligned}$$

It should be noted that:

$$D_T = \frac{N_D}{56{,}000 \text{ b/s}} = \frac{N_D + 32n}{64{,}000 \text{ b/s}}$$

where n = the total number of SOM's required for the length of the data packet

N_D = # of data bits

Each SOM is 32 bits.

2.2 Channel Problems and Modem Modifications

When the basic system described above is used for the transmission of packet data certain problems arise which affect channel performance. These problems have been difficult to diagnose because they typically have involved interaction mechanisms between the two participating stations. That is, an individual station would work well when it operated in loopback mode through the satellite, i.e., hearing its own transmissions. Good performance was also typically obtained when one station transmitted and the other received. The problems tended to occur when both stations were active in transmission and reception. In the discussion to follow two of the problems of this nature will be considered along with the corrective actions taken.

In addition to problems of the above type, the packet mode of transmission tends to stress the acquisition circuitry of the modems more than voice transmission. In particular it requires better modem acquisition performance. This in turn implies more stringent control of modem adjustment to ensure that all its subunits are operating within their specified operating ranges.

Developing techniques to identify the symptoms associated with subunits whose parameters or performance are out of specification has required appreciable Comsat effort. Additional effort has been expended on scheduling and coordinating the required engineering tests at the earth stations and in some cases performing tests in the laboratory.

2.2.1 Problems Associated with Multiple Station Operation

The bursts received at the earth station are down converted from the 4 GHz band to a 70 MHz IF by the earth station down converters, and sent to the SPADE IF sybsystem. The particular channel of interest is picked out and down converted a second time to 512 kHz in the channel modem. The signal is demodulated and the two channels of data, at 32 K Baud, and the 32 kHz bit timing clock are sent to the Receive Synchronizer.

Two circuits in the modem, viz., the AGC and VCO units, which operate well for burst mode voice transmission, do not perform adequately for the reception of burst mode data as it is being used in the ARPA circuit. The primary differences in the operation of the channel for "burst mode voice" vs "burst mode data" are related to the dynamics of channel usage. For voice, reception is from one station only, and the time between bursts is on the order of seconds. For data transmission, as employed by the ARPA channel, reception is from two stations, and the time between bursts is, under certain conditions, less than a millisecond.

The implications of this change in channel operation and its effect on the operation of a SPADE channel unit can be explained as follows.

Effect on AGC

The AGC amplifier continuously samples the level of the 512 kHz IF and adjusts it to be a constant output through the use of negative feedback from the level detector. The characteristics of the level detector are such that it has a short acquisition time constant but a long release time constant. Figure 2-3 shows the AGC feedback voltage relative to the incoming burst. The photograph (Figure 2-3) was taken at the Etam, W.Va. earth station.

This AGC characteristic has caused two types of channel problems. For non contention protocols, those that involve only a single station transmitting at any time, the observed behavior is missed packets if there is a power imbalance between the two stations' transmissions. In particular, if the lower power station transmits a packet immediately following a transmission from the higher power station there will be a tendency for the modems to miss the packet because their AGC circuits will not respond rapidly enough and the preamble and SOM will be received at low levels. Power imbalances on the order of 1.5 to 2 dB were observed to cause this problem. For contention protocols, those that involve simultaneous occupancy of the satellite transponder,

(a) Received Burst
(512 kH_z IF)

(b) Feedback Voltage
Unmodified AGC
Circuit

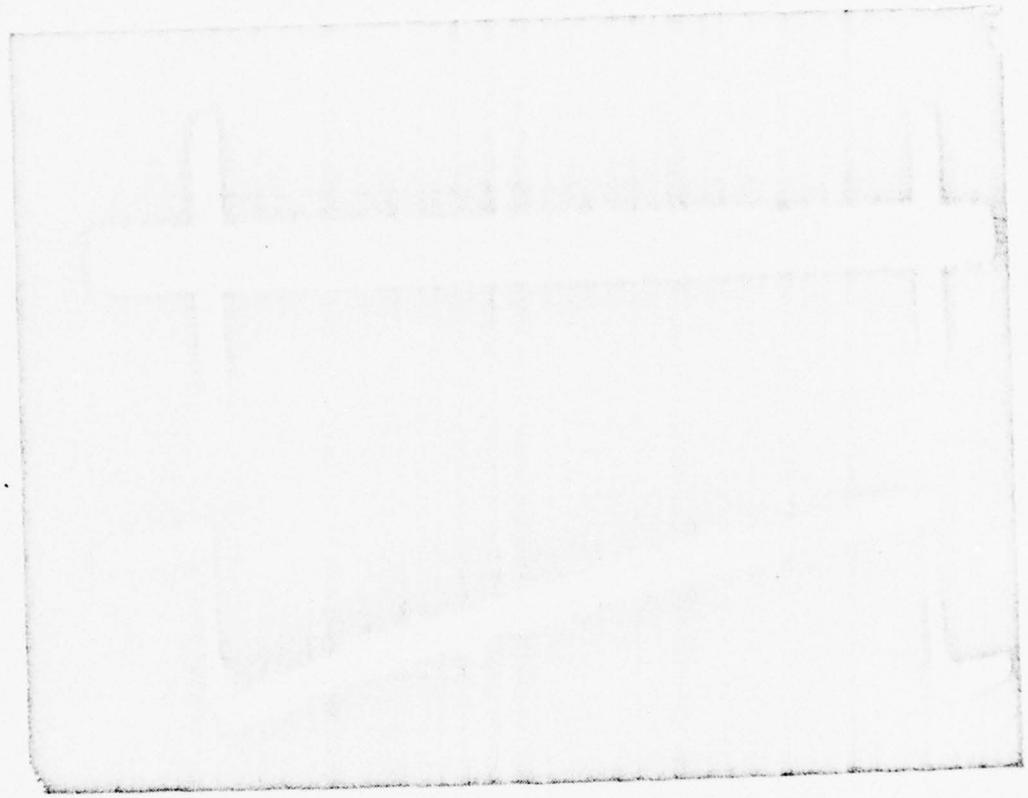

FIG. 2-3 AGC FEEDBACK VOLTAGE

a similar problem occurs. The packets that are in contention are of course not correctly received, but, in addition, due to the above AGC characteristic the packet in the next slot also tends to be missed, even when not in contention, due to the 3 dB power increase associated with the contention slot.

The power imbalance problem has been alleviated by more stringent and frequent monitoring of the stations' transmit powers. This is essentially a procedural change. In addition, the AGC circuits have been modified so that any power imbalance that does exist should not cause a problem and measurements with contention protocols can be performed.

Tests, at COMSAT's request, were made at the Goonhilly earth station, and subsequently that AGC circuit was modified. A definite improvement in AGC acquisition and release times was obtained. Similar modifications were made at the Etam earth station after some additional testing. Figure 2-4 (a-c) compares the AGC feedback voltage for the unmodified and modified AGC amplifier. The top trace (a) shows the feedback voltage of the modified AGC amplifier, and the bottom trace the feedback voltage of the unmodified amplifier. Figure 2-4(c) shows, with an expanded scale, the feedback voltage for the modified AGC amplifier.

Additional measurements were performed on the modified AGC to determine the release time of the AGC as a function of input power levels, viz., a burst with a nominal C/N and a second burst 9 dB higher than nominal. Figure 2-5 shows the results of those measurements. As shown in the figure it would take less than 2 msec for the AGC to decay to the value of feedback voltage normally obtained for a burst of nominal value. A signal strength of 9 dB above nominal would be equivalent to having eight earth stations simultaneously transmitting

a) Modified AGC

b) Unmodified AGC

FIG 2-4 FEEDBACK VOLTAGE
AGC CIRCUIT
(Signals Inverted)

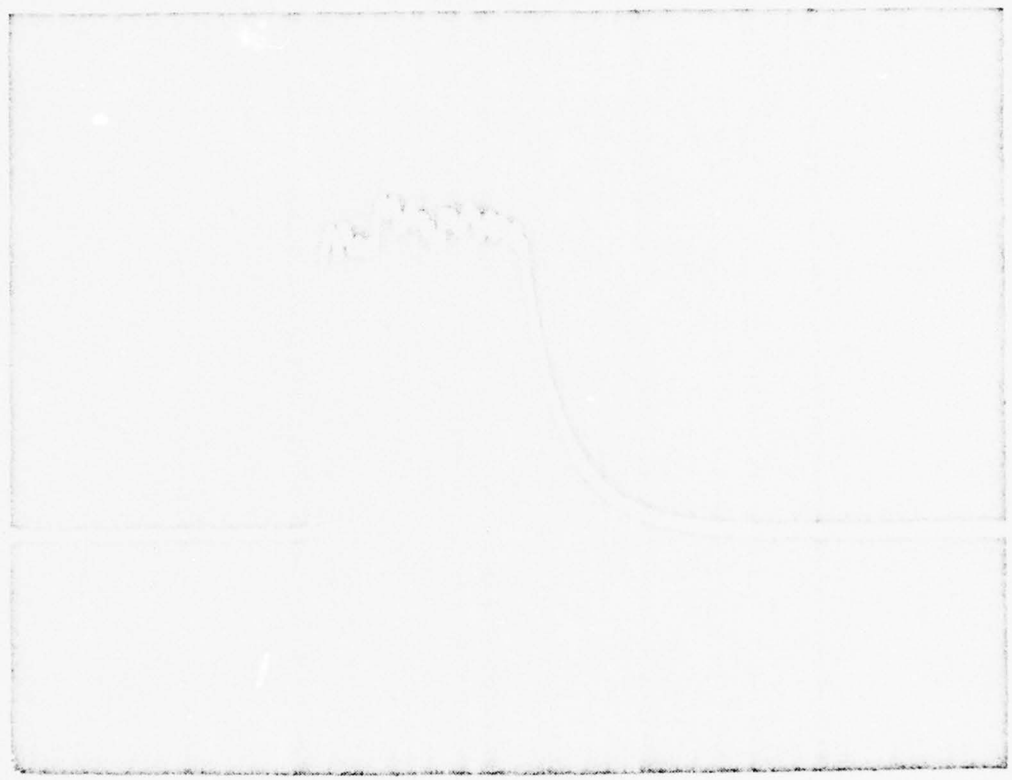

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FIG 2-4(c) FEEDBACK VOLTAGE
MODIFIED AGC CIRCUIT (Expanded Scale)
(Signal Inverted)

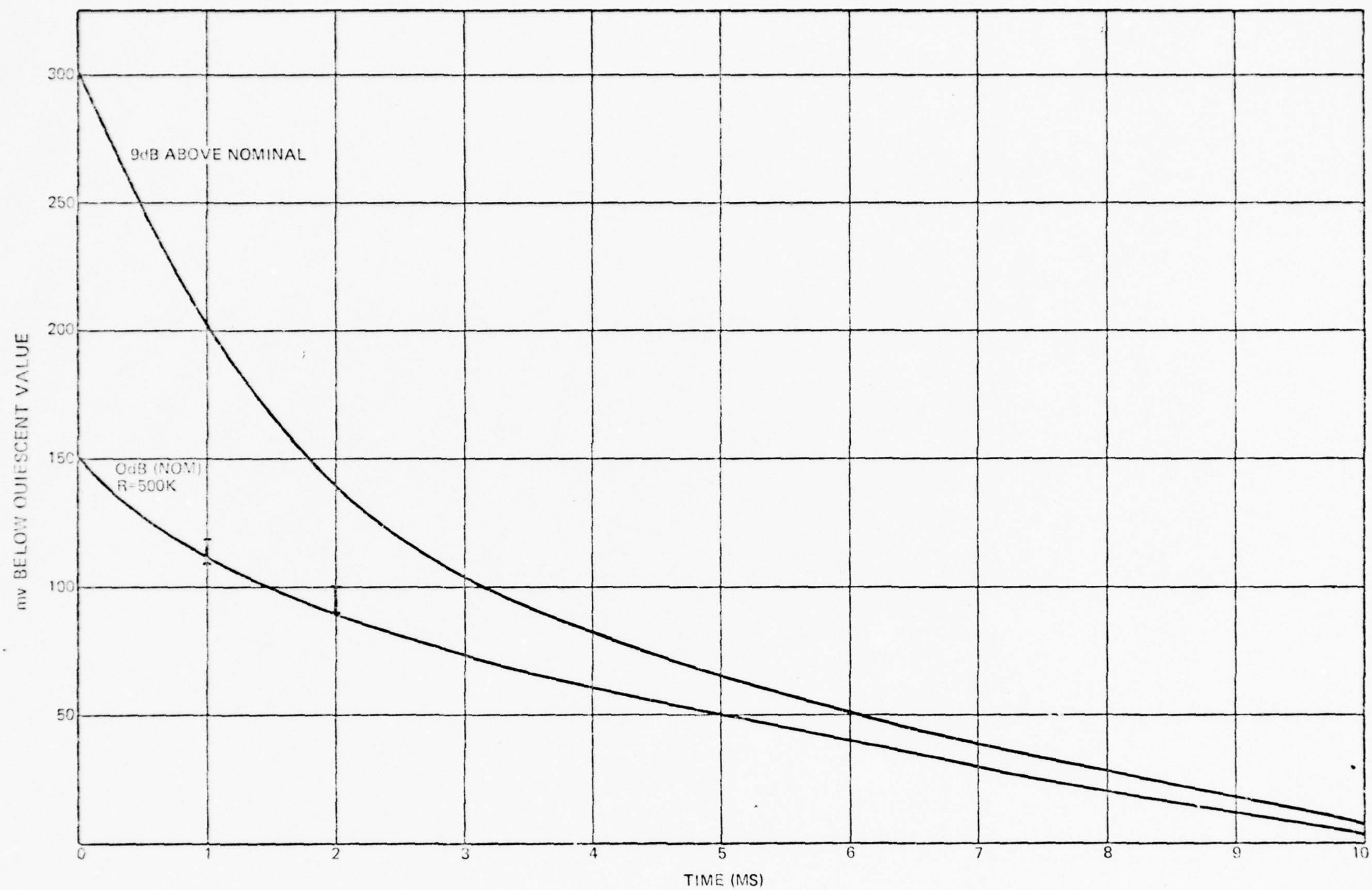

FIGURE 2-5 MODIFIED AGC CIRCUIT DISCHARGE VOLTAGE VS TIME FOR TWO IF SIGNAL LEVEL INPUTS.

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through the satellite.

Additional testing is being done at COMSAT Laboratories on the SPADE modem AGC. The purpose of the testing is to better understand the characteristics of the AGC circuit and to determine what further improvements can be made in AGC operation to provide better reliability in the satellite circuit and minimize the guard time requirement. Preliminary results indicate that the decay time can be reduced to a few bit times.

Effects of VCO Offset

The Voltage Controlled Oscillater (VCO) provides a 512 kHz reference signal for demodulation of the input burst. Since bursts arriving from different earth stations will not have been transmitted at exactly the same frequency, due to slight differences in earth station up-converter frequencies, the modem VCO must compensate for these differences. The oscillator control is set at 8.192 MHz. Its output is tunable and controlled by a loop filter which determines the amount of correction necessary to produce a zero frequency difference between the modulated IF and the reference. The reference 512 kHz signal is obtained from the 8.192 MHz oscilattor by dividing its output by 16.

Figure 2-6 shows the output of the loop filter, i.e., the control voltage to the VCO, with reference to alternating input bursts from the two stations. The difference in this voltage is proportional to the difference in frequencies of the signals arriving from two different earth stations. With no signals into the modem, the output of the loop filter tends to decay to and remain at a quiescent voltage level in anticipation of the next burst. Under normal SPADE operation, bursts are separated by large guard bands and some bits

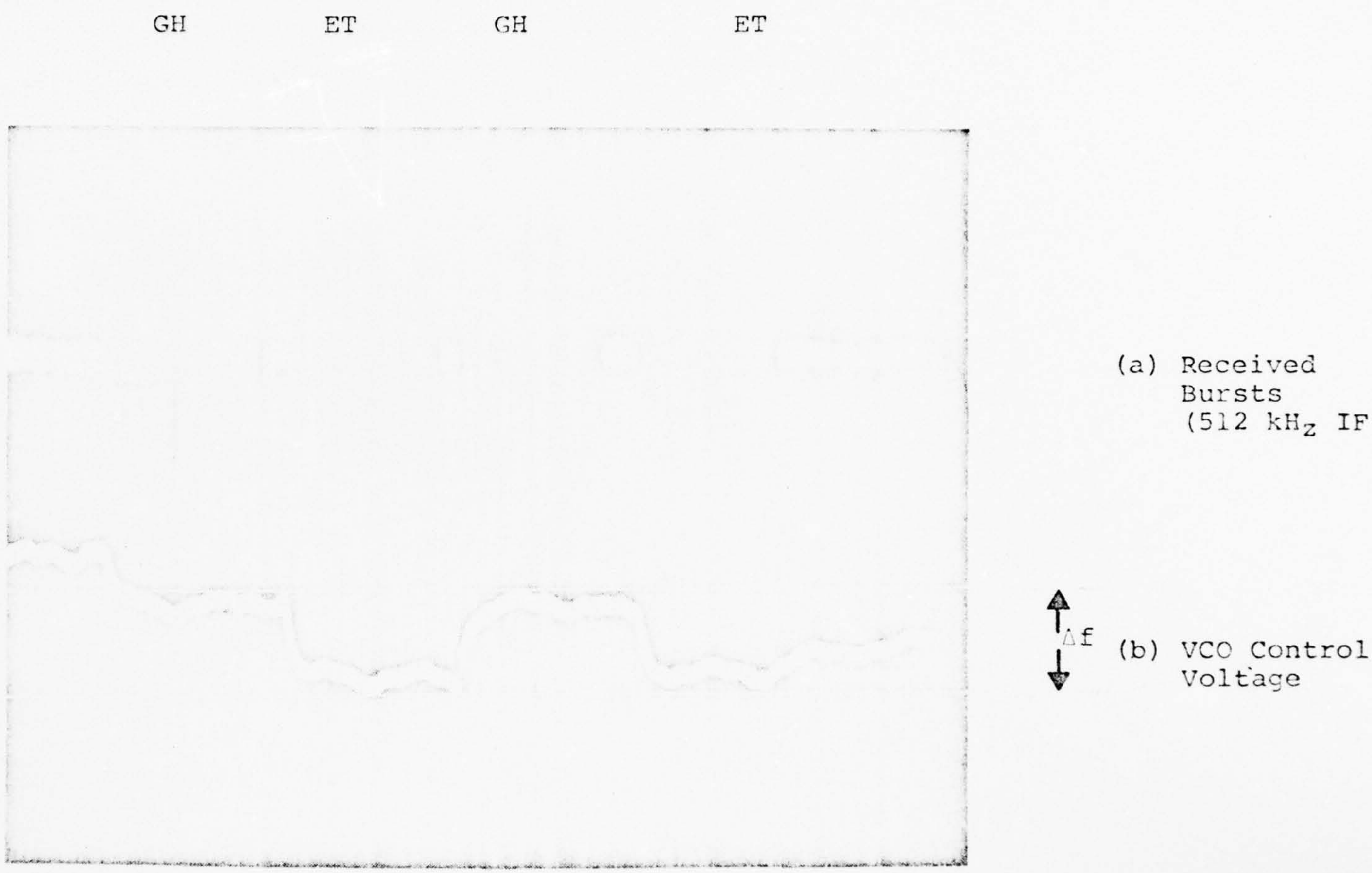


FIG 2-6 VCO CONTROL VOLTAGE

can be missed on a burst without much performance degradation. Also bursts will tend to be received from the same station for a significant time period. In the packet mode, transmissions will rapidly switch from station to station and all data bits must be correctly received if the packet is not to be missed. Under these conditions the loop filter must adjust rapidly if there is any appreciable frequency difference between the transmissions of the two stations. If the station transmission frequencies are not carefully controlled and the modem VCO's carefully adjusted there will be a tendency to miss packets.

To prevent this type of channel problem the transmission frequencies of the two stations must be carefully monitored and the channel performance must be monitored for any signs of VCO misadjustment. The frequency of measurements on the relative transmit frequencies has been increased to ensure that the difference is maintained within the 200 Hz SPADE system specification.

The SPADE System specification requires all stations in the SPADE system to maintain their up-converter frequency within 200 Hz of the Etam, W.Va. earth station. (Etam is used as the system reference.) Thus, the maximum frequency difference between bursts that one should expect with two stations in the network would be 200 Hz. However, once a third station is brought into the network, the maximum frequency difference could be as much as 400 Hz, causing an even greater demand on the VCO loop filter. Additional investigations into the operation of the VCO and loop filter will be required to better understand its limitations and capabilities, and to determine what modification should be made, if any, to improve its operation.

2.3 Modifications to the SSI

Two changes in the circuitry of the SSI were made in order to eliminate two possible causes of marginal operation. The first change was to shift the position of the 56 kHz clock relative to the leading edge of the data sent to the SIMP. In the original design the leading edge of the clock and the leading edge of the datum bit were coincident. In transmitting the clock and data pulses from the SPADE channel unit to the SIMP, some distortion or delay could be introduced into one of the signals. As a result, the possibility existed for the data written into the SIMP to not be properly synchronized with the clock. In order to prevent this from occurring, the position of the clock was moved so that its rise and fall times occur in the middle of the bit. Hence, the data being written into the SIMP is in a definite high or low state, rather than possibly in transition from high-to-low or low-to-high.

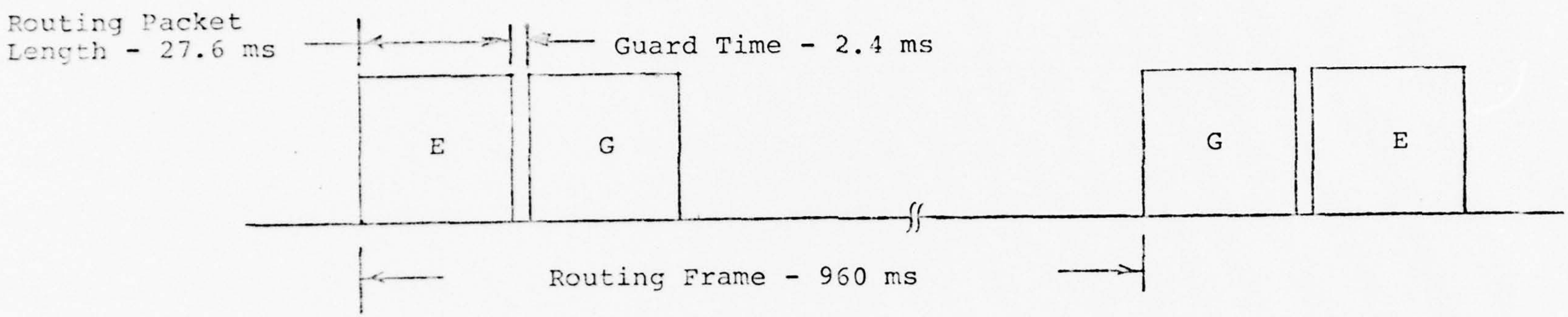
The second modification incorporated into the SSI was a change in the timing for turning the carrier on relative to the start of the preamble. In designing the interface unit it was assumed that if the carrier was turned on prior to generating the preamble this additional carrier energy would aid in the carrier recovery. The normal carrier recovery sequence is 20 bits of all "1's" sent to the A and B channels of the modem. The first 1 is coincident with the start preamble ($\overline{SP}$) pulse. By turning on the carrier prior to the $\overline{SP}$ pulse, the bit sequence was changed to eight 0's followed by twenty 1's. Additional testing showed that this procedure did not improve the carrier acquisition time. If anything, it degraded the acquisition time since the modem would first try to lock into one reference phase and then invert the reference phase when the signal went from zero-to-one. Therefore, the extended preamble time was removed.

2.4 Channel Monitoring and Remaining Channel Problems

The various equipment and procedure modifications considered above have greatly improved the channel performance for packet, i.e., burst data, operation. There is, however, at least one factor that continues to limit the achieved performance.

The channel performance is monitored 24 hours per day by the transmission of 'routing packets' by each SIMP, with a period of approximately once per second. In particular the channel transmissions, the absence of other data packets, are as shown in Figure 2-7. Note that the two routing packets are contiguous and alternate order from routing frame to routing frame. Each routing frame consists of 32 slots which are 30 milliseconds in length. The routing packets occupy 2 of the 32 slots and are 27.6 milliseconds in length in terms of the duration of R.F. energy. Thus there is a guard time of 2.4 milliseconds between routing packets.

The SIMPs record the channel performance by monitoring the number of 'routing packets' which are received over a fixed time interval, which are typically four minutes long. In particular each SIMP records the number of its own routing packets that it correctly received when it transmitted first, the number of its own routing packets that it correctly received when it transmitted second, the number of the other SIMP's routing packets that it received when the other SIMP transmitted first, and the number of the other SIMP's routing packets that it correctly received when the other SIMP transmitted second. These values are compared to the expected number of receptions in each category and the difference is recorded as the number of missed packets in that category. The typically used 4-minute interval corresponds to 128 packets of each type, i.e., each SIMP sends a total of 256 packets



E - ETAM TRANSMISSION
G - GOONHILLY TRANSMISSION

(Figure Assumes No Data Packets on the Channel)

FIG 2-7 ROUTING PACKET TRANSMISSION

per interval. The SIMP also records the number of packets that are received with hardware check sum failures during the measurement interval. As far as check sum failures, all routing packets, own or other guy's, and any data packets, own or other guy's, that might be transmitted are treated alike, with just the total number of check sum failures recorded. If the total number of routing packets missed in all categories at a given SIMP exceeds 4 during the measurement interval, the data is made available through the Network Control Center at Bolt, Beranek, and Newman. If the number of missed routing packets is equal to or exceeds four, the data also indicates whether the number of check sum failures in the measurement interval was ≤ 3 or ≥ 4, by setting a single binary bit. The software to perform this channel monitoring was developed by Bolt, Beranek, and Newman.

This channel monitoring information can be used to diagnose certain channel and equipment malfunctions and anomolies. During any measurement interval when the number of missed packets exceeds the threshold value of four the available data # has the form shown in Figure 2-8. The resulting data patterns can be viewed as syndromes of particular types of channels problems. For example the pattern

1:V,W/X,Y X, Y, U and V approximately equal

tends to occur for one of the stations if the bit timing (32 MHz) voltage controlled oscillator (VCO) in its modem is not within its specified operating range. Similarly, prior to the AGC modifications the pattern (syndrome)

0:0, X/0,0	Etam	$X \geq 4$
0:0, 0/0,X	Goonhilly	

would result if there was a significant (several dB) power imbalance between the Etam and Goonhilly transmissions with Goonhilly relatively

U:V, W/X, Y

- Separate measurements of the above form are made for each station during each measurement interval.
- V = # of own 'routing packets' not heard when transmitted first.

  W = # of own 'routing packets' not heard when transmitted second (i.e., the other station's transmission goes first).

  X = # of other station's 'routing packets' not heard when they are transmitted first.

  Y = # of other station's 'routing packets' not heard when they are transmitted second.
- Measurement is recorded if $V + W + X + Y \geq 4$, otherwise not.
- If the measurement is recorded, U = 1 if 4 or more check sum errors occur, otherwise it is 0.

Figure 2.8 Data Format of Channel Monitoring high.

Analysis and monitoring of these missed packet patterns has proven to be a useful method of quickly spotting and correcting certain equipment and operational anomalies.

As the result of appreciable diagnostic work, improvements in operational procedures to fit this type of channel usage, and the use of the channel monitoring information, the channel is now relatively free from performance degradation (e.g., missed packets) that can be attributed to systematic, equipment related, causes.

The channel does, however, still exhibit one type of impairment. The channel performance, as determined by the number of missed packets, seems to exhibit a two state behavior. It is either in a 'good' state where misses are very unlikely or a 'bad' state where misses are much more likely and characterized by the average syndrome

Etam 0: X,Z/X,Z $\qquad$ $X > Z$ and $U \geq X$, $V \geq Z$

Goonhilly 0: U, V/U, V $\qquad$ $U > V$

There is a correlation between the behavior at Etam and Goonhilly and a tendency to miss first packets, in a sequence of two, whether transmitted by yourself or the other station. Figure 2-9 shows the measurement statistics for an average day and illustrates the occurrence of this syndrome. See specifically entries at 0833, 0838, and 0842.

Further, the tendency to be in the 'bad' state is time of day dependent and also tends to vary somewhat from day to day. Figure 2-10 illustrates the time of day dependence of the performance for a typical 24 day period. To obtain the data used to plot this figure, the number of packets missed during each hour period at each station were counted for each of the 24 days. Then for each of the twenty-four

```
Simp Report
0314  G 0: 5,0 / 0,0

0343  G 0: 5,0 / 2,0

0347  G 0: 2,0 / 3,0

0500  E 0: 6,0 / 13,1
      G 0: 18,2 / 16,1

0505  E 0: 9,2 / 25,0
      G 0: 21,0 / 16,0

0535  E *(101, 3, 2)

0537  E 0: 3,3 / 7,6
      G 0: 3,3 / 7,6

0541  G 0: 7,0 / 3,0

0833  E 0: 1,0 / 4,0
      G 0: 4,0 / 2,2

0838  E 0: 26,7 / 35,2
      G 0: 42,9 / 37,6

0842  E 0: 32,1 / 33,1
      G 0: 37,6 / 40,5

0846  E 0: 1,0 / 3,0
      G 0: 7,0 / 3,0

0858  E 0: 2,0 / 10,0
      G 0: 10,0 / 6,1

1219  G 0: 0,0 / 8,0

1320  G 0: 2,0 / 4,0

1324  E 0: 5,0 / 3,0
      G 0: 10,0 / 13,0

1328  E 0: 8,0 / 3,0
      G 0: 22,0 / 29,0

1353  G 0: 6,0 / 13,0

1552  E 0: 8,0 / 2,0
      G 0: 17,0 / 24,0

1556  E 0: 13,0 / 3,0
      G 0: 13,1 / 22,0

1600  E 0: 5,0 / 3,0
      G 0: 16,0 / 18,0

1705  E 0: 6,0 / 4,0
      G 0: 11,0 / 12,1

1710  E 0: 32,0 / 16,2
      G 0: 41,0 / 42,0

1714  E 0: 9,0 / 3,0


      G 0: 15,0 / 11,0

1759  E 0: 10,0 / 0,0
      G 0: 6,0 / 16,0

1815  E 0: 13,0 / 2,0
      G 0: 9,0 / 24,0

1819  G 0: 6,0 / 13,0
```

FIG 2.9 – Measurement Statistics

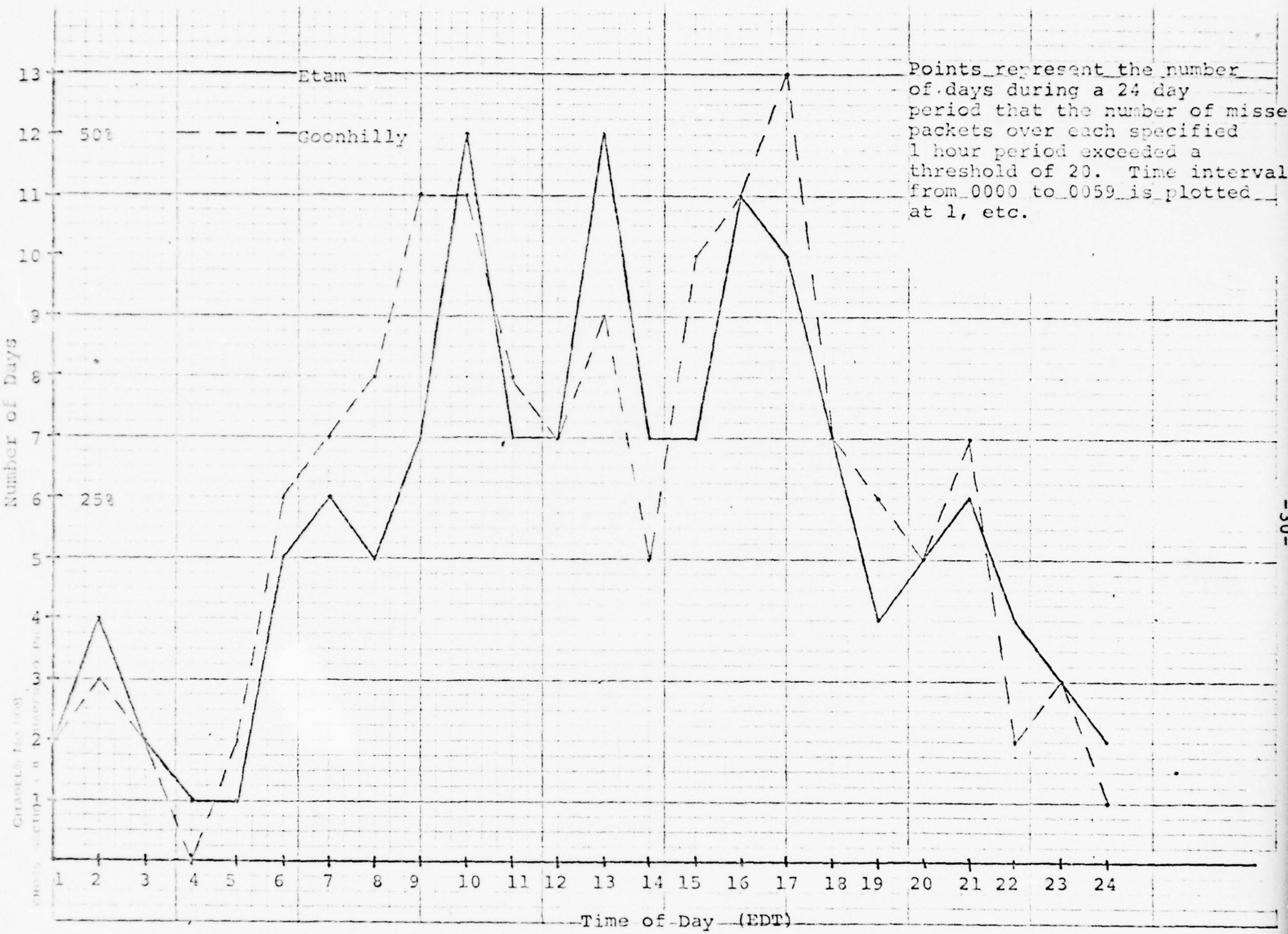


FIG 2-10 CHANNEL MISSED PACKET PERFORMANCE vs TIME OF DAY FOR 24 DAY PERIOD

one-hour periods the number of days during which the number of missed packets, of all types, at a specific station exceeded twenty was counted, this data was then plotted on an hour by hour basis for each station.

There is reason to believe that this performance is somehow related to the total activity in the SPADE transponder through a non linear coupling mechanism. This behavior is not completely understood at this time. Further, its transient nature makes measurement difficult.

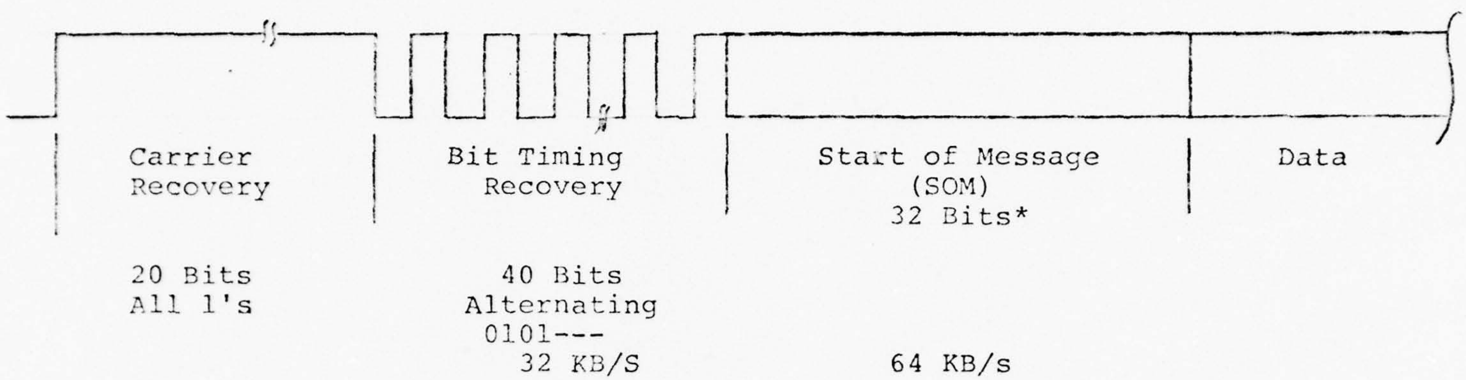
2.5 Channel Performance Analysis

To provide a background for the interpretation of the channel monitoring described above, some analysis of the channel behavior in a noise dominated environment was performed. In order for the SIMP to correctly acquire a routing packet the SPADE modem must acquire the carrier frequency and bit timing from the burst preamble and detect the presence of a unique word (start of message (SOM) indicator) which is used to resolve phase ambiguity. The SOM consists of two 16 bit words which must be detected with at most 2 bit errors. The preamble and SOM format is shown in Figure 2-11. At this point bits are read into the SIMP and all 1264 bits in the routing packet must be correctly received to count as an acquired routing packet.* If the SIMP unique word 'SYN DLE STX' corresponding to the bit pattern

$$\overbrace{0000,0010}^{\text{STX}},\overbrace{0001,0000}^{\text{DLE}},\overbrace{0001,0110}^{\text{SYN}}$$

is received but there is an error in any of the remaining bits then the packet will not be counted as a received 'routing packet' but will be counted as a packet with a check sum failure. If 'SYN DLE STX'

*The eight bits immediately following the SOM are not important and can be arbitrary.



*SOM SEQUENCE: 00001001000100000111101101110010

FIG 2-11 PREAMBLE/SOM FORMAT

is not correctly received, the SIMP ignores the packet completely.

For simplicity in what follows it will be assumed that the modem acquires each packet, i.e., it achieves carrier and bit timing acquisition and SOM detection. Further it will be assumed that the error probability for each of the information bits in the basic packet (the bits that are used by the SIMP) is uniform. Both of these results will tend to bias the analysis in the direction of being optimistic. Indeed, one result of the analysis will be to indicate that the probability of modem acquisition must be appreciably less than unity in certain situations to account for the experimental data. The uniform error probability assumption is not entirely realistic either, because the later bits in the packet normally benefit from the additional time available to the modem to refine its carrier and bit timing estimates. While the difference in error probability might be a factor of 10 or more, useful results can be obtained with the uniform assumption.

With the above assumptions the performance analysis reduces to a binomial probability analysis. Let p represent the probability of a bit error and n the number of bits in a routing packet. Then the probability of acquiring a routing packet is

$$p_a = [1-p]^n$$

and the probability of missing the packet is

$$p_m = 1-p_a$$

Each measured statistic consists of four types of measurements:

(1) number of misses when listen to self and transmit first,

(2) number of misses when listen to self and transmit second,

(3) number of misses when listen to other station and it transmits first, and

(4) number of misses when listen to other station and it transmits second.

Assuming that bit errors are equally probable in the four types of measurements and independence between measurement types and measurements of a given type,

$$P_{no} = \text{Prob of no output in measurement interval}$$

$$= \text{Prob } [\sum_{i=1}^{4} \ell_i < 4]$$

$$= \sum_{\substack{\ell_1, \ell_2, \ell_3, \ell_4 \\ \epsilon \sum_{i=1}^{4} \ell_i < 4}} P(\ell_1)\, P(\ell_2)\, P(\ell_3)\, P(\ell_4)$$

$$\text{where } P(\ell_i) = \binom{N}{\ell_i} P_a^{\,N-\ell_i}\, P_m^{\,\ell_i} \quad 0 \leq \ell_i \leq N$$

is the probability of missing ℓ_i packets of type i and N is the number of packets transmitted during the measurement interval. The above result reduces to

$$P_{no} = P^4(0) + 4\,P^3(0)\,P(1) + 4\,P^3(0)\,P(2) + 4\,P^3(0)\,P(3)$$
$$+ 6\,P^2(0)\,P^2(1) + 12\,P^2(0)\,P(1)\,P(2) + 4\,P(0)\,P^3(1)$$

With the above results it is possible to consider the number of recorded statistics that should be contained on the channel performance record obtained each day from the Network Control Center at Bolt, Beranek, and Newman as a function of the bit probability of error. Figure 2-9 is an example of such a record. In particular, for each station,

$$\text{Average Number of Outputs} = 360\,[1-P_{no}]$$

$$\text{Variance in Number of Outputs} = 360\,P_{no}\,[1-P_{no}]$$

and

$$\text{Prob } [j \text{ outputs}] = \binom{360}{j} P_{no}^{\,360-j}\,[1-P_{no}]^j$$

assuming a measurement interval of 4 minutes, or 360 measurements per day.

Table 1 summarizes these results as a function of p for n = 1264 and N = 128. This N value corresponds to the 4 minute measurement interval and the transmission of a routing packet by each station approximately once per second, i.e., each station sends 256 routing packets in the measurement interval. Independent measurements of p normally yield a value in the range 10^{-6} to 10^{-7}. Thus it is clear that the ordinary thermal noise effects do not account for the typically observed behavior such as shown in Figure 2-9. Because of the absence of check sum errors, it seems that the probability of the modem not acquiring the preamble must be significant under certain transponder conditions. As mentioned earlier, the exact cause of this phenomenon is not yet completely understood.

3.0 Design Efforts to Improve System Hardware

In the area of design efforts to improve system hardware, two specific design efforts were preformed. The first concerned the design of a new SPADE/SIMP Interface unit. This effort was motivated by the desire to increase the reliability, flexibility and throughput of the channel. The new design, if implemented, should accomplish these goals.

The second design effort concerned an evaluation of several ways to eliminate the requirement for simultaneous use of two SPADE channel units at each station. The new designs would provide satisfactory service with the use of a single channel unit. There would, however, be a potential availability problem unless a redundant channel unit can be made readily available. The motivation for this effort was the potential shortage of channel units at some earth stations, Goonhilly in particular, and some potential operational simplicity advantages to confining operation to a single channel unit.

ρ	ρ_{no}	Avg. No. of Outputs	Var. in No. of Outputs	Prob (j outputs)				
				$j=0$	$j=1$	$j=2$	$j=3$	$j>4$
10^{-5}	0.117134	3.18×10^{2}	3.72×10	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	$<10^{-8}$	1.0
10^{-6}	0.996312	1.33	1.32	2.6×10^{-1}	3.5×10^{-1}	2.3×10^{-1}	1.0×10^{-1}	4.6×10^{-2}
10^{-7}	0.999992	2.7×10^{-3}	2.7×10^{-3}	9.97×10^{-1}	2.9×10^{-3}	4.1×10^{-6}	3.5×10^{-9}	-

TABLE 1 EXPECTED CHANNEL MISSED PACKET PERFORMANCE vs BIT ERROR RATE

(ASSUMES MODEM ACQUISITION WITH PROBABILITY ONE)

Some thought has also been given to the development of a test and monitoring capability as an adjunct to the SSI. The operational experience to date suggests the need for a real time test and monitoring capability as an aid to channel fault diagnosis and to obtaining a complete understanding of channel performance in the packet mode of operation. Such a capability would permit a close correlation between channel performance and the measurement data taken on the performance of various demand assignment algorithms.

3.1 New SIMP/SPADE Interface Design

One task under the contract was to determine how the system operation could be improved over the original design concept, i.e, the low risk approach with the minimum number of modifications to the SPADE channel units. A complete new interface has been designed and bench tested. The new interface eliminates the uncertainty in time associated with the transmission of the data out of the SIMP relative to the GOSIG, and the overhang time required to insure all the data have been cleared from the memories upon reception. The new interface design also increases the transmission rate from the SIMP from 56 KB/s to 64 KB/s. Finally the new interface is expected to facilitate a significant increase in channel reliability by placing the control of preamble generation in the interface unit rather than in the SPADE channel unit. It is believed that the simplest way to overcome the channel problem discussed in Section 2.4 is to use a longer preamble. The new interface design, which can include an essentially arbitrary preamble, would facilitate such a change and hence potentially have a significant effect on channel reliability. Modifying the preamble in the current system is not feasible as it would require a complete redesign of the transmit synchronizer of the SPADE channel unit.

The new interface design incorporates all the functions necessary for transmission and reception of the burst. The functions necessary for transmission include preamble and SOM (Start of Message) generation, carrier on/off control, and transmission of 64 kHz clock pulses to the SIMP. The receive interface accepts the two 32 KB/s data streams from the modem, resolves the phase ambiguity of the data streams, and recombines the two 32 KB/s data streams into a single 64 KB/s data stream to be transmitted to the SIMP.

The increase in the transmission speed from the SIMP to 64 KB/s is accomplished by eliminating the requirement to insert a 32 bit SOM between every 224 bits of data. The purpose of inserting the 32 bit SOM is two-fold; for transmission it is used for "bit stuffing" to increase the transmission rate from 56 KB/s to 64 KB/s; and for reception, the 32 bit SOM is to resolve any phase ambiguity of the voice data in the event of cycle slip or loss of phase lock. The reception of data in the packet mode requires synchronization of the data starting with the first data bit. Should data be received in error, for whatever reason, then the entire packet is discarded and a new transmission of the packet requested. Hence, after initial synchronization of the data by the first SOM, any loss of data due to cycle slip or loss of phase lock, which would be corrected by subsequent SOM's, is of no value for the packet mode of transmission. Therefore, it is possible to eliminate all SOM's from the data stream except for the first one. This SOM is used for initial synchronization and resolution of any phase ambiguities. After synchronization is established by detection of the first SOM the modem must remain locked for the duration of the burst, otherwise the packet is discarded. This is the same restriction on phase lock as was required by the receive synchronizer in the present SPADE channel unit.

The only significant delay in the new interface design is the delay between the GOSIG and the transmission of data from the SIMP to the interface. This delay, 2.375 μsec if the present preamble and SOM are used, is required for generating the preamble and SOM. A second delay between 5.57 and 7.8 μsec is necessary for set-up time of the transmit interface after receipt of the GOSIG from the SIMP. Figure 3-1 shows the block diagram and timing relations for the new interface configuration. This figure shows the present preamble and SOM, but the interface design will permit the use of any length preamble and SOM within the constraints of the hardware implementation. These constraints are 255 bits (max.) of carrier and bit timing recovery, and fixed length per channel SOM's of 16,20, 24, or 28 bits. In this configuration the present SSI and the SPADE Transmit and Receive Synchronizers would not be used. The new transmit and receive interface units perform all the functions necessary for transmission and reception of the burst.

3.2 Single Channel Unit Design

A second investigation was made to determine what modifications would be necessary if a single channel unit were employed rather than two units as in the present configuration. To employ a single channel unit for the ARPA circuit either a second synthesizer must be installed or a shift of 18.045 MHz of one output signal from the synthesizer must be performed. The first approach, i.e., the use of a second synthesizer, was rejected as being too costly to implement. The second approach, i.e., frequency shift, in its initial concept is shown in Figure 3-2. This configuration presents a problem in that the isolation between mixer input and output ports is not perfect. As a result the input from the frequency synthesizer will feed through the mixer and appear at the output at levels as high as 22 db below the desired fre-

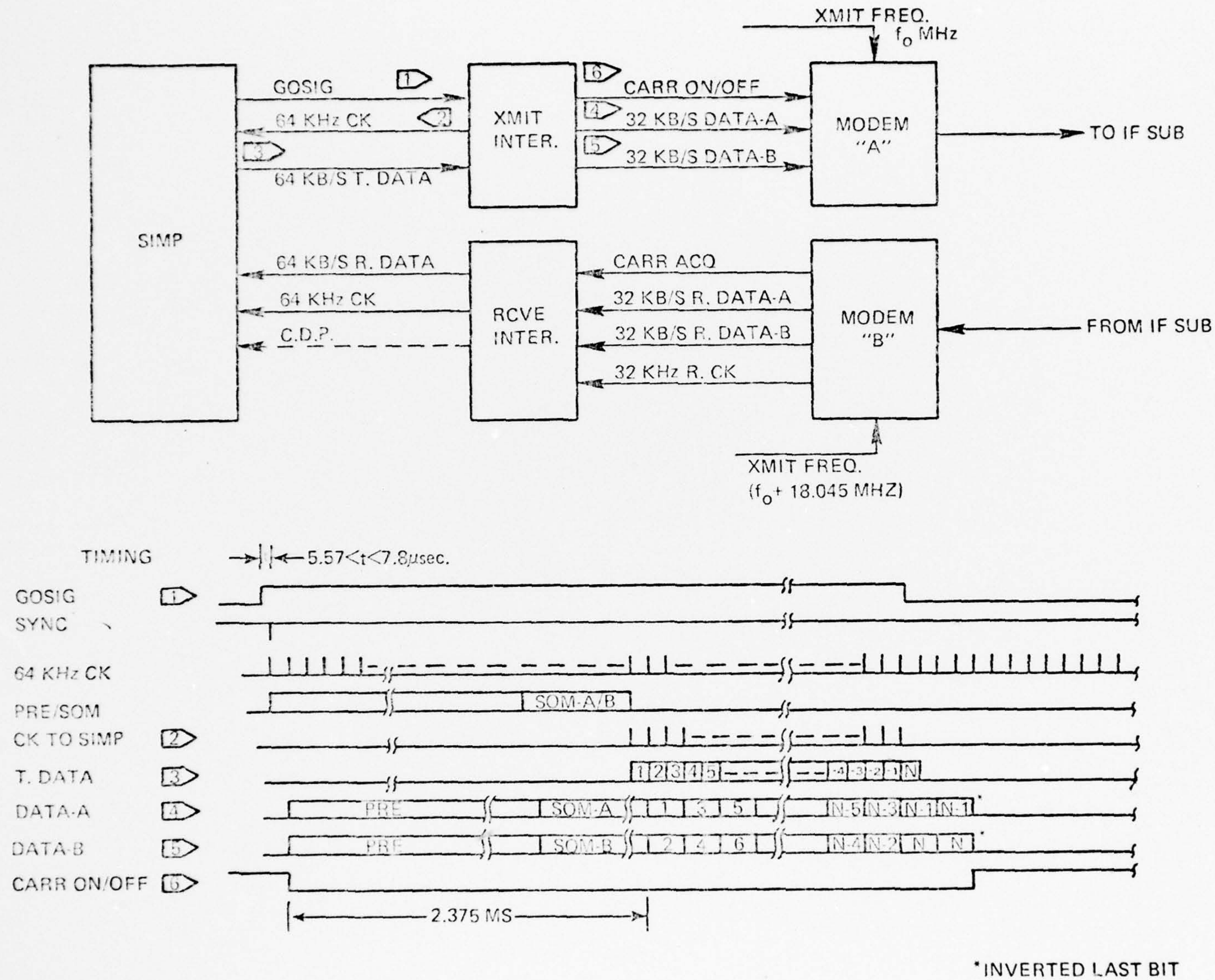


FIGURE 3.1 PROPOSED SYSTEM BLOCK DIA.

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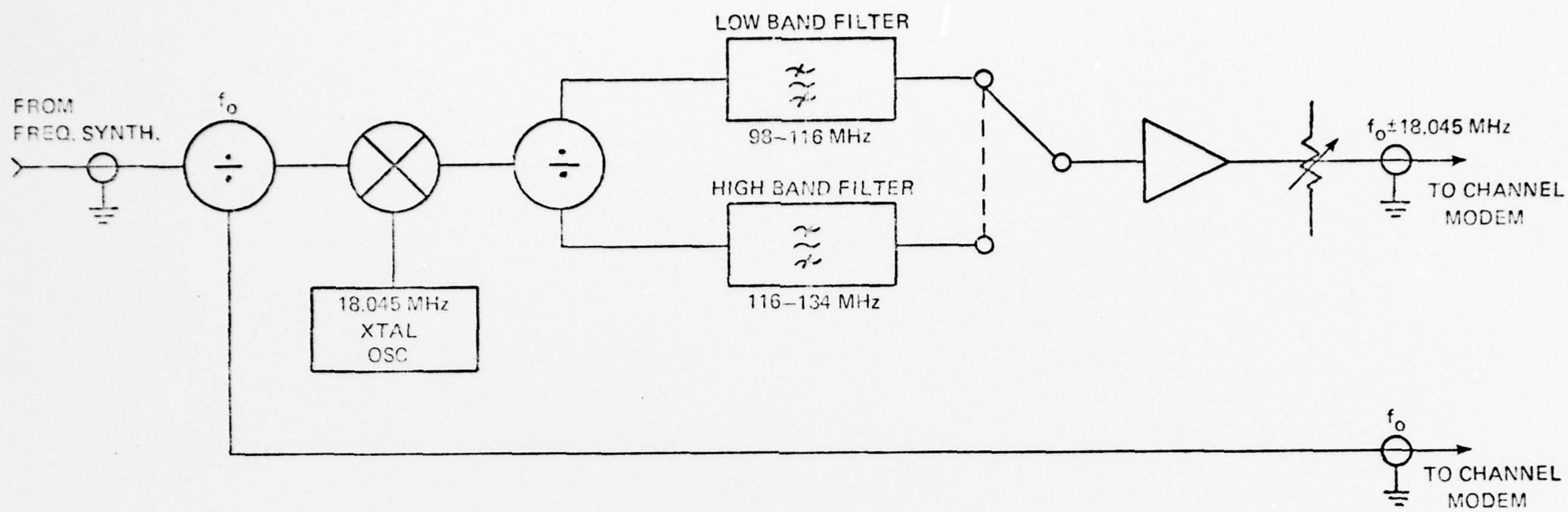

FIGURE 3.2 PROPOSED FREQUENCY CONVERTER–BLOCK DIAGRAM

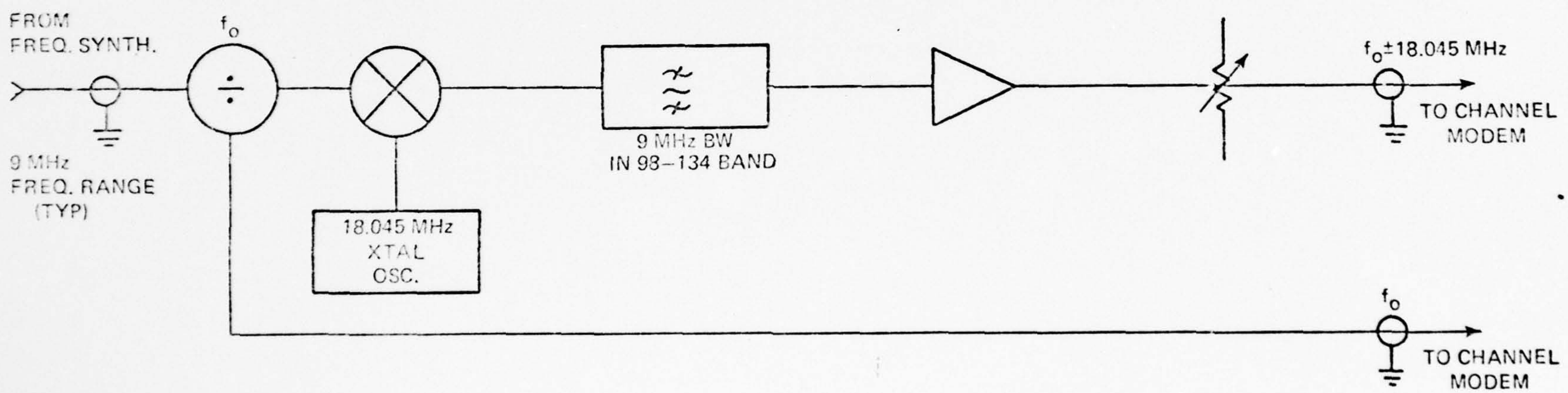

FIGURE 3.3 RESTRICTED FREQUENCY RANGE SYSTEM

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quency. If the desired signal is near the band edge of either the high band or the low band filter, each of which has better than 18 MHz bandwidth, the input frequency, which is 18.045 MHz away from the desired signal and 22 db below it, will be within the filter passband.

This interference can be reduced by either of the following two methods:

1. Restriction of the transmission frequency range so that narrower bandwidths can be used in the high and low band filter's, or
2. Double conversion of the transmit frequency in which the frequency synthesizer output is translated upward by a large enough amount so that the input frequency is not within the filter passbands and is then down converted by a frequency which is 18.045 MHz above the upconversion frequency.

Block diagrams for the two methods are shown in Figures 3-3 and 3-4. The combination of oscillators shown in Figure 3-4 was chosen to take advantage of the 46 MHz oscillator already existing in the earth terminal modulator. In either method the filters will have to have less than 0.5 db variation over the range of frequencies transmitted and will have to attenuate the interfering frequency by at least 20 db. This means that the unwanted signal passing through the mixer will be at least 42 db below the desired frequency at the filter output.

The oscillator stability should be an order of magnitude greater than the frequency synthesizer stability specified by the SPADE System Specification. This specification requires $\pm$ 50 Hz on the Frequency Synthesizer output. Assuming that the oscillators have a stability of $\pm$ 2 Hz (so that the combination of both oscillators is less than $\pm$ 5 Hz), the highest frequency oscillator (64 MHz) shown in Figure 3-4 would

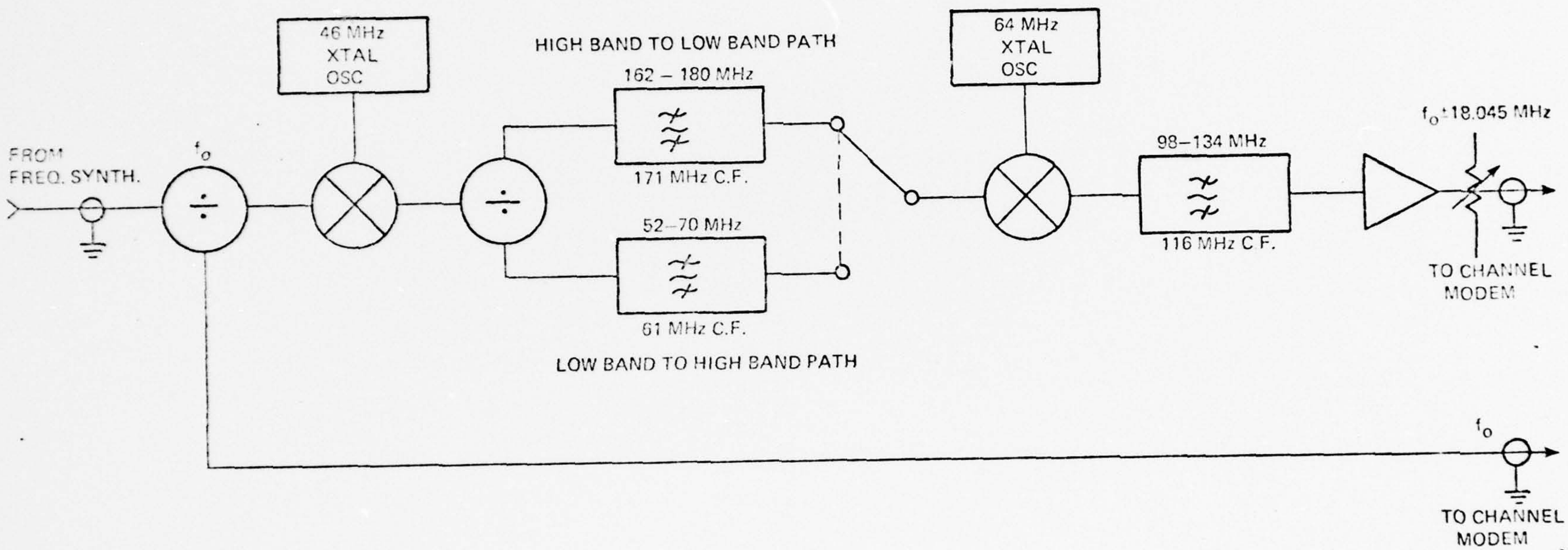

FIGURE 3.4 DOUBLE CONVERSION SYSTEM

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have to have a stablility of better than 3 parts of 10^8: The 18.045 MHz oscillator used in the restricted frequency range method would require a stability of approximately 2 parts in 10^7.

All filters, oscillators and mixers needed for either of these approaches are readily available commercially. Longest lead time items would be the oscillators which require 12 weeks ARO for delivery.

In order to maintain complete flexibility in frequency assignment, the double conversion approach would be required, should this technique be implemented. The disadvantage to modifying only a single channel unit is that, in the event of failure, there would be no back-up channel unit available. The cost to implement, install, and document this change would be approximately $3200 per channel unit.

3.3 Proposed Test and Monitoring Module(T&M)

As experience was gained by monitoring and evaluating the system performance, it became evident that additional equipment should be incorporated into the interface units to dynamically test and monitor the system performance at each earth station on essentially a packet by packet basis. Real time evaluation of system functions would significantly aid the earth station personnel involved in the maintenance of the system, in addition to aiding the personnel involved in evaluating the performance of the experimental satellite network.

The information would be collected in two general categories. The first would be status information which would be in a digital format. This data would contain information as to carrier acquisition, bit timing, SOM detection, receive data rate, hardware check sum errors, etc. The second category of data would involve monitoring modem performance, and be of an analog format. The analog data would be converted to digital data for transmission to the SIMP. In monitoring the modem performance each station would have to calibrate its own modem outputs and the "calibration curves" would be stored in the SIMP. An updating of the calibration curves would have to be performed routinely. The information collected from the modem could include AGC feedback voltages, information on noise levels, VCO control voltages for the 512 KHz and 32 KHz (Bit Timing) oscillators, etc. The test and monitoring module should also provide a means for determining a conflict, i.e., when two or more stations simultaneously contend for the time slot. A control word from the SIMP would be used to determine what function is to be measured at the next received burst. Contention data would be continuously monitored and the information sent to the SIMP after each detected conflict. The information would be sent to the SIMP over a dedicated line installed between the SIMP and the T&M module. The T&M module would be installed into the SPADE channel unit shelf.

4. Conclusions

The initial concept of using the SPADE System for the transmission of packet data via satellite has been proven to be feasible. The low risk approach used in the modification of the channel units and in the implementation of the interface units facilitated the initial testing of the system. It also proved valuable in determining what the shortcomings were in using the SPADE type channel units and what should be done to improve their operation.

The experience gained in the operation of the system to date has shown that continued engineering support will be required to evaluate and improve system operation. This will be particularly true as new earth stations are added to the network. The equipment and procedural modifications which have been made have significantly improved the reliability of the channel. The present level of channel performance is not a significant impediment to the experimental activities. There are, however, remaining channel performance problems which will require additional analysis and corrective measures.

It is recommended that the SIMP/SPADE Interface units be modified in two important ways. A modification to the data transmission portion of the interface, as discussed in Section 3,will improve the system flexibility, reliability and throughput. Of particular importance would be the provision within the modified unit of capabilities for flexible preamble and SOM generation and SOM detection. This capability would permit preamble and SOM modifications which are expected to be important in removing the remaining channel performance problems.

The second recommended modification is to incorporate a real time test and monitoring module into the SSI. As discussed in Section 3.3, such a capability would be very valuable for both system maintenance and as an aid to the experimenters in evaluating the performance of a satellite packet communication system.

Annex 1

List of Definitions

CODEC - Coder-Decoder - Used in the SPADE channel unit for converting analog voice signals to 56 KB/s data during transmission, and during reception to convert the 56 KB/s data back to analog voice signals.

DTS - Data Test Set - Test equipment designed and built by COMSAT under an ARPA contract, to measure channel bit error rate and channel continuity in burst mode operation.

GOSIG - A signal generated by the SIMP to indicate when the SIMP is ready to transmit data.

PREAMBLE - A bit sequence, generated in the transmit synchronizer, composed of the carrier recovery sequence, 40 bits of all "1's", followed by the bit timing recovery, 80 bits of alternating 00110011.... The bit rate is 64 KB/s.

Transmit Synchronizer - One of the modules in the SPADE channel unit. This module performs a number of functions, including the generation of all timing signals and clocks, preamble and SOM generation, carrier on/off control, and contains the modem drivers.

SIMP - Satellite Interface Message Processor - A Honeywell 316 mini-computer modified by Bolt, Beranek and Newman for use in the ARPA satellite experimental program.

SOM - Start of Message - A 32 bit data sequence generated in the Transmit Synchronizer and used by the Receive Synchronizer to resolve phase ambiguities in the data received from the modem. The SOM is inserted into the data stream after each 224 bits.

$\overline{SP}$ - Start Preamble - Synchronizing pulse generated in the Transmit Synchronizer which turns on sequence generators to generate the preamble and SOM's.

SPADE - Single channel per carrier PCM Multiple Access Demand Assignment Equipment.

SPADE Channel Unit - A part of the SPADE terminal composed of a number of sub-modules for the transmission and reception of a single carrier through the SPADE system.

SPADE SYSTEM - An international demand assignment multiple access communications system utilizing SPADE equipment.

SPADE Terminal - The equipment used at an earth station for access to the SPADE System.

SSI - SIMP/SPADE Interface - Equipment designed and built by COMSAT for use in the ARPA Satellite experiment. The SSI is placed between the SIMP and SPADE channel units and used to exchange and condition the signals passed between the two.

T&M Module - Test and Monitoring Module - A module being considered to aid the experimenters and earth station personnel in evaluating and monitoring the performance of the satellite channel.

Receive
Synchronizer - One of the modules in the SPADE channel unit. This module receives the demodulated data from the modem, resolves any phase ambiguities in the data streams, and then transmits the 56 KB/s serial data and 56 KHz clock to the SIMP, via the SSI.